Research Statement
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My research goals center around the need for phenomenology in cosmology: the art and science of showing how theories affect observations of large-scale structure and the cosmic microwave background (CMB), and to some extent, *vice-versa*.

This is an ideal time to be a phenomenologist in cosmology. The volume of high-precision data compiled within the last 15 years from CMB and type IA supernovæ observations, and from galaxy and Lyman-α forest surveys, has significantly advanced our understanding of the Big Bang and subsequent structure formation. But it also has yielded unexpected discoveries which highlight how much more work there is to do on the theoretical front. For example, the puzzle of the origin and behavior of dark matter, now a nearly undisputed if ill-understood component of the standard paradigm, has been complicated by the need for a "dark energy" component to explain cosmological acceleration evident in type IA supernovæ redshift surveys.

In those same 15 years, we have also seen N-body simulations reach a dynamic range capable of probing galaxy formation within a cosmological context due to the tremendous increase in available computing power (and its correlated decrease in cost). In the last few years, my research has increasingly required the use of such tools.

1 Numerical Action Methods

1.1 Space Interferometry Mission Dynamics of Galaxies (SIMDOG)

When the Space Inteferometry Mission (SIM) satellite is launched, it will have unprecedented precision (4 μ-arcsecond/yr) to enable a search for stellar systems likely to have extrasolar planets. This will lay the foundation for the subsequent Terrestrial Planet Finder satellite which will be precise enough to find earth-like planets around such sytems. As a side benefit to the primary mission, this same precision will enable the measurement of the transverse velocity of up to ∼30 nearby galaxies to within 20 km/s/Mpc. Currently, only two transverse velocities for galaxies IC10 and M33 have been measured [1]. Having tens of such measurements to 2- or 3-σ will allow an analysis of the local flow in three dimensions, putting much greater limits on local densities.

We have been using Numerical Action (NA) methods [2] to model the growth of structure at the local level: on the scales of a few-to-tens of Megaparsecs around the Milky Way. NA is not limited to simple linear models of the growth of structure. By using the principle of least action on full cosmological gravity, NA can predict nonlinear interactions and even orbits. If given accurate enough position and velocity data, NA can be used to constrain the ratio of mass to light (and by extension, the density) in the local volume.

1.2 Voids

- The local peculiar motions of galaxies is simply modeled as mostly driven by gravitational collapse of dark matter overdensities in a smooth background. Real large-scale velocity fields are a complicated system traced by galaxies of this collapse, and include measurable accelerations due to local voids. In a recent paper [**?**], we examined the evidence that the peculiar velocity of the local group is due in part to its position relative to a sizable local void.

1.3 Initial Conditions: from Stochastic to Realistic

• Recently, we have begun to address the problem of how to run an N-body simulation which recreates the structure we actually see, rather than creating a model which is simply in statistical agreement with our data. "Constrained simulations" are available in the literature but have yet to reproduce the local group in convincing detail. Recent examples of NA show the power of using real data to probe the dynamics of the local volume [3]. In a sense, NA solves for orbits backward in time from the data given. Thus it can be used to "predict" what initial conditions are necessary to create the local structure we see. We are currently in the process of creating a "data pipeline" which uses real galaxy position and velocity catalogs to generate likely initial conditions. Those initial conditions can then be used by an N-body simulation, such as the publically avaialble GADGET code [4], to (re)create the halos and associated galaxies today. Thus, we hope to close the loop between observations and simulations on scales approaching the separation of the Milky Way from M31 (Andromeda) ($\sim$0.7 Mpc). Preliminary work indicates that this is achievable with very little parallelization. With a detailed history of their nascent environment and evolution, we can better understand galaxy characterstics such as the mass-metallicity and morphology.

1.4 NA and Turnaround Densities in ΛCDM

• Numerical Action (NA) has undergone extensive revision since it was first introduced. In my first two years at Maryland, I have rewritten and extended a Numerical Action method code and created extensive analysis tools to characterize the results. One product of this has been the generation of a semianalytic functional form for turnaround density in a ΛCDM paradigm universe which was presented at the Winter 2007 AAS meeting.

Turnaround occurs when the Hubble flow between two objects (caused by the generic expansion of the universe) is equal and opposite to their relative peculiar velocity. The standard observational example is when a galaxy has just begun to "fall in" to a galaxy cluster or group instead of expanding away with the general Hubble flow. This has been used (*e.g.*, [5]) to estimate the mass of the group/cluster as a whole based on a simple set of formulæ seen in any cosmological textbook. However, the closed analytical form available presumes a universe with only matter (dark or light) and curvature. The inclusion of a dark energy component renders the formula invalid. We show that because the equations remain scale invariant, the simple semianalytic fit we derive to the turnaround density equations for a ΛCDM universe is valid for any scale [6].

2 Large Scale Structure

After the cosmic microwave background, large scale structure is the best candidate for a precision cosmology probe. The distribution and dynamics of galaxies and galaxy clusters give a direct probe into the cosmological parameters of structure growth. Galaxy clusters are particularly useful since the dominant importance of gravitational effects implies that certain properties should be calculable from first principles.

2.1 Peculiar Velocities

• I have shown that a catalog of galaxy cluster peculiar velocities from a kinetic Sunyaev-Zel'dovich type experiment probes the growth of structure in a nontrivial way [7]. Previous efforts had suggested that such a catalog could be used to constrain Ω_m almost independently of the Hubble parameter, h, or the dark energy equation of state parameter w [8]; it was anticipated from linear theory models that the bulk velocity rms for galaxy clusters would rise with larger values of Ω_m. By simulating multiple clusters in different cosmologies, I showed that the rarity of clusters in lower Ω_m universes implies they exist in extreme environments; this causes the rms velocity to increase above linear expectations for lower values of Ω_m and renders the overall dependence on Ω_m to be very small.

2.2 Weak Lensing

• Cosmic shear, the statistical presence of excessive shear in background galaxies, is sensitive to the presence of dark energy. Binning the shear by redshift ("tomography") helps constrain evolution of the dark energy equation of state. Due to projection effects, there is a considerable amount of cross-correlation between different redshift bins. We have worked on a method which attempts to decorrelate bins by directly using galaxy cluster information from other sources, such as future cluster surveys using the thermal Sunyaev-Zel'dovich effect [9].

3 Cosmic Microwave Background (CMB)

The CMB is still the best probe for understanding early cosmology and the seeds of structure formation. Designing and analyzing experiments which can use the CMB to discriminate between models has become a large industry and I have enjoyed making useful contributions.

3.1 Computational Hurdles

• Determining the angular power spectrum of the primary anisotropy in the CMB (C_l^T) from large datasets such as those from NASA's Wilkinson Microwave Anisotropy Probe (WMAP) and ESA/NASA's Planck satellites is a computational challenge. We have shown that this challenge can be met by devising and optimizing a "divide and conquer" method of heirarchical decomposition [10].

3.2 Backgrounds

• It has been demonstrated that the kinetic Sunyaev Zel'dovich effect from the Milky Way is a negligible background for the temperature anisotropies [11]. I have been investigating how much it may add to the polarization background [12].

4 The Future

Despite the overwhelming observational successes of WMAP and the Sloan All-Digital Sky Survey (SDSS), there is still a great deal of exciting cosmology ahead. Studying cosmic shear on an extremely large scale is necessary for probing dark energy. When built, the Large Survey Synoptic Telescope will provide unprecedented volumes of data at the low optical distortion needed to measure galaxy-galaxy lensing and statistical cosmic shear. When built and launched, the Supernovæ Acceleration Probe (SNAP) will not only greatly increasing the number of measured type IA supernovæ (and at deeper redshifts), it will also provide the necessary low optical distortion and wide fields necessary for studying cosmic shear, a complementary probe of dark energy. A large challenge for both of these projects will be in constructing the data pipeline and in effective modelling of the data; two areas in which I have developed many skills.

Constrained N-Body simulations will increase in accuracy as computer speed increases, and simultaneously, as the distance and velocity catalogs of the local (nearest ∼40 Mpc) volume improve. I have developed the very tools needed to address these challenges and look forward to shifting the view of N-body work as something in statistical agreement with reality to becoming a direct model of reality. We can then begin to address environmental issues of galaxy formation based on real data.

In summary, there is no end in sight for the work of phenomenology in cosmology, a pleasant prospect for any science, and for me in particular.

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